ERDC/CERL TR-00-3

US Army Corps of Engineers®
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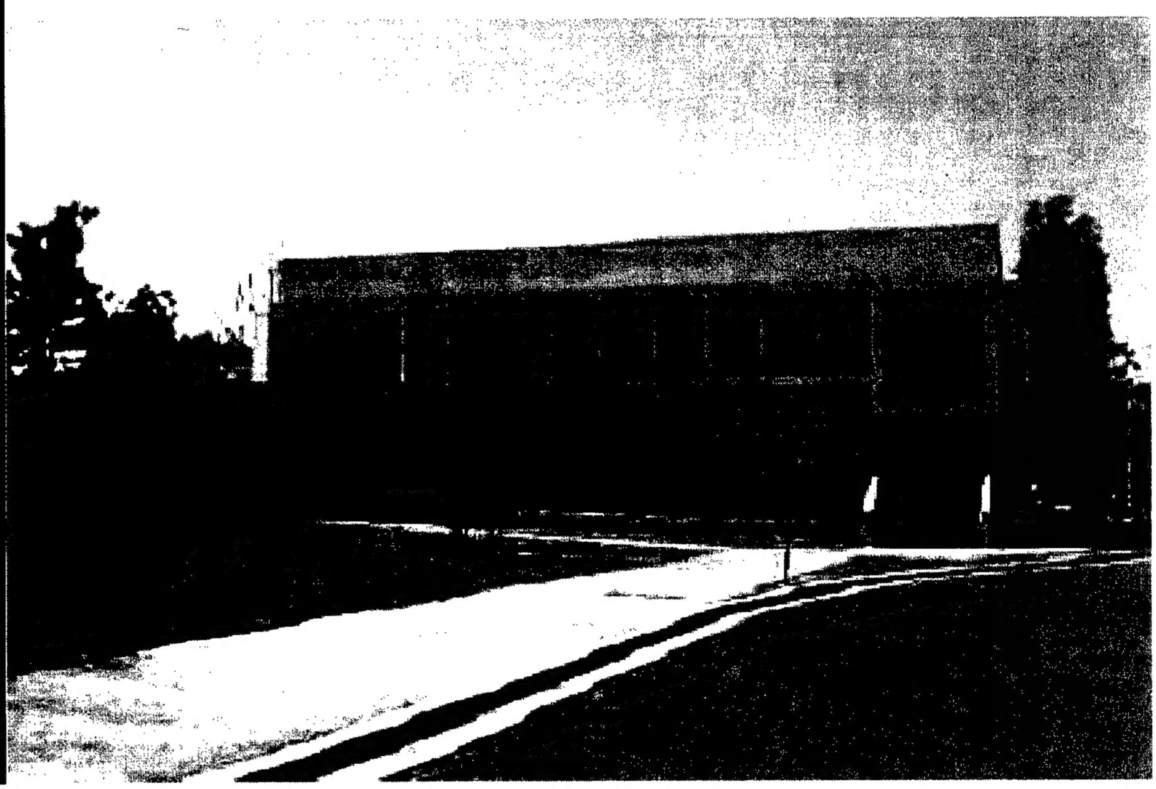
Assessment for Desiccant Cooling Air-Conditioning at Antilles High School, Fort Buchanan, Puerto Rico

Moisture Load Analysis of the Gymnasium Building

Jaynary Barreto-Acobe and Martin J. Savoie

January 2000



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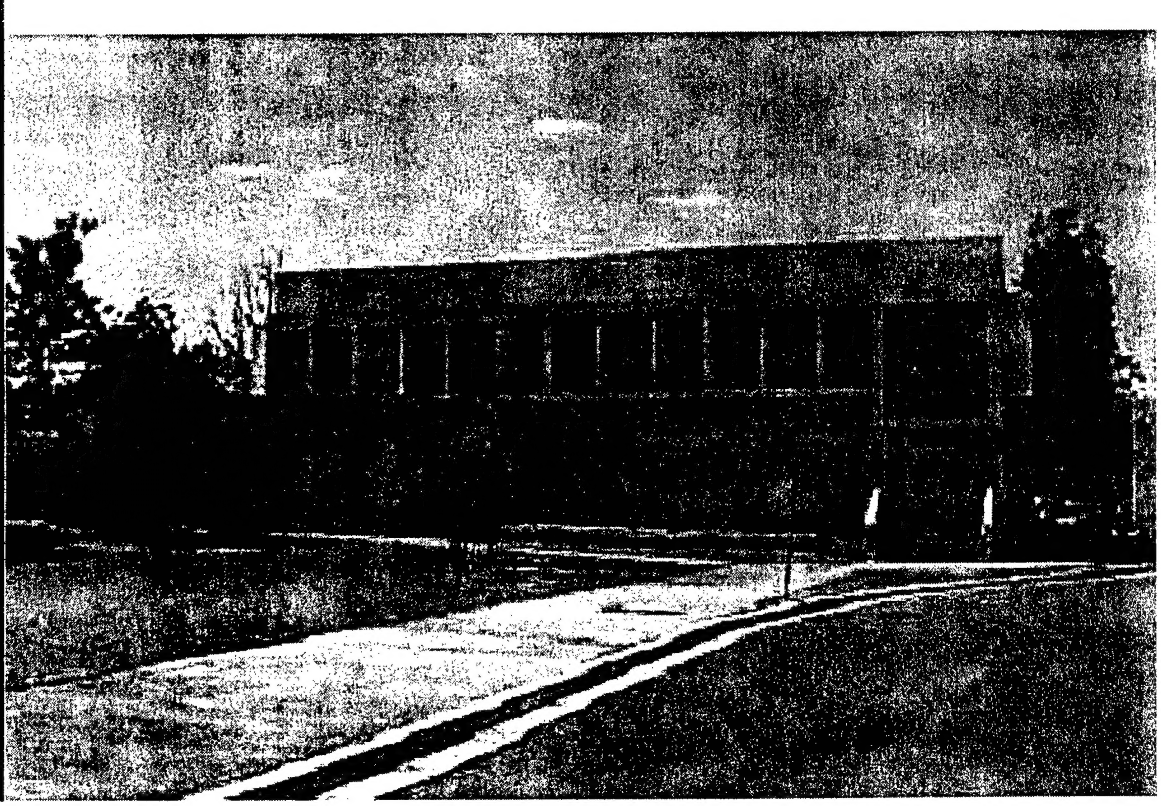

Construction Engineering Research Laboratory

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Foreword

This study was conducted for Antilles High School, Fort Buchanan, Puerto Rico, under Military Interdepartmental Purchase Request (MIPR) HEPRAN-99RCL1031, "Condition Assessment and Recommendations for the Replacement of HVAC Controls and Related Systems at Antilles High School, Fort Buchanan, Puerto Rico," dated 9 June 1999. The technical point of contact was Rafael Negron, Facilities Engineer.

The work was performed by the Energy Branch (CF-E), of the Facilities Division (CF), U.S. Army Construction Engineering Research Laboratory (CERL). Jaynary Barreto was a student associated with the University of Puerto Rico at Mayaguez, under the Committee for Institutional Cooperation's "Summer Research Opportunities Program" (SROP). The CERL principal investigator and SROP monitor was Martin J. Savoie. This program allows academically promising students the opportunity to conduct research in their discipline, within a mentored environment. Special thanks is owed to CERL researchers Larry Lister and David Schwenk for their technical contributions to this study. Larry M. Windingland is Chief, CEERD-CF-E, and L. Michael Golish is Chief, CEERD-CF. The CERL technical editor was William J. Wolfe, Information Technology Laboratory. The Acting Director of CERL is William D. Goran.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Director of ERDC is Dr. James R. Houston and the Commander is COL James S. Weller.

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1 Introduction

Background

The U.S. Department of Defense (DOD) actively supports good education for the dependents of its personnel and, for this reason, created the Department of Defense Education Activity (DoDEA). The U.S. Army Corps of Engineers, together with DoDEA, are working to improve educational facilities in schools like Antilles High School (AHS) in Puerto Rico at Fort Buchanan. One such project is the design of a new air-conditioning system that will improve comfort inside the high school gymnasium. The school's classrooms and gymnasium offices are air-conditioned with a standard heating, ventilation, and air-conditioning (HVAC) system that uses a Freon®-based air-conditioning system. Due to the high temperature and high relative humidity common to Puerto Rico, it is desirable to implement an air-conditioning system that can maintain a controlled temperature of 75 °F and a 50 percent relative humidity.

To achieve effective results at a low cost, "desiccant cooling" technology will be used in this application. This system was considered because it can dehumidify the air entering the treated space, reduce the relative humidity, and result in lower operating costs than could a comparable conventional system with reheat, where the cost of electricity is high compared to natural gas (the fuel typically used as the energy source for desiccant regeneration). "According to one estimate, desiccant dehumidification could reduce total residential electricity demand by as much as 25 percent in humid regions, providing a drier, more comfortable, and cleaner indoor environment with a lower energy bill." A necessary preliminary step before specifying a desiccant cooling system is to perform a moisture load analysis of the area to be cooled. This study documents the moisture load analysis of the gymnasium Building at AHS.

Objectives

The overall objective of this work was to perform an assessment of the HVAC system at AHS, to provide a written summary of the system's condition, and to make recommendations for system improvement, including a detailed cost estimate of a system upgrade. The objective of this part of the work was to perform

a moisture load analysis of the Gymnasium Building at AHS to determine the required capacity of the desiccant cooling air-conditioning system to be installed.

Approach

1. A literature search was done to find the required standard moisture load calculations, and temperature and moisture data relevant to Puerto Rico.

2. Total moisture load was calculated by summing all possible moisture sources for the gymnasium area, for all its various levels of use.

3. Recommendations were made regarding the capacity of the proposed desiccant cooling system based on these calculations, current usage patterns, and the assumption that, once the Gymnasium Building is air-conditioned, it is likely to receive increased use.

Scope

This study focuses specifically on the Gymnasium Building at AHS, Fort Buchanan, PR. However, the methodology and calculations used in this study are broadly applicable to similar sites, especially those in similar geographic locations.

Mode of Technology Transfer

This information is to be provided directly to the Antilles Consolidated School System. It is also anticipated that this information will be made available through CERL's world-wide web (WWW) at URL:

http://www.cecer.army.mil.

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 sq in.	=	6.452 cm^2
1 sq ft	=	0.093 m^2
1 sq yd	=	0.836 m^2
1 lb	=	0.453 kg
°F	=	(°C x 1.8) + 32

2 Description of Desiccant Technology

Desiccants are a class of materials that attract, hold, and directly remove moisture from the air. There are two basic types of desiccants: solid and liquid. A solid desiccant, like silica gel, is placed inside a "honeycomb wheel," also called a "desiccant wheel." However, liquid desiccant is sprayed into the air to remove moisture. The proposed system for the AHS gymnasium will use a desiccant wheel (Figure 1). Humid air from the outside, also called "process air," enters the wheel where it is dried by the solid desiccant. After that, the dry air is cooled by an HVAC system connected to the wheel, and finally it flows throughout the treated space. There is a second air stream called "reactivation air" that could come from either inside or outside the cooled space. The desiccant wheel is driven by an electrical motor that rotates very slowly so the reactivation air can dry the desiccant, and then repeat the cycle by absorbing moisture again when it rotates back to the process air.

Designing a desiccant system requires a moisture load analysis. This analysis quantifies the moisture that will enter the treated space and therefore the moisture that the system will remove. At AHS, this analysis used a moisture load calculation methodology developed by Cargocaire Engineering Corporation (Munters Cargocaire 1990). Figure B1 shows the worksheet used to calculate the total moisture load. The first analysis made was the vapor transmission into dehumidify space or permeation, that is the moisture that passes through the walls, ceiling, and floor and that depends on the porosity of the material.

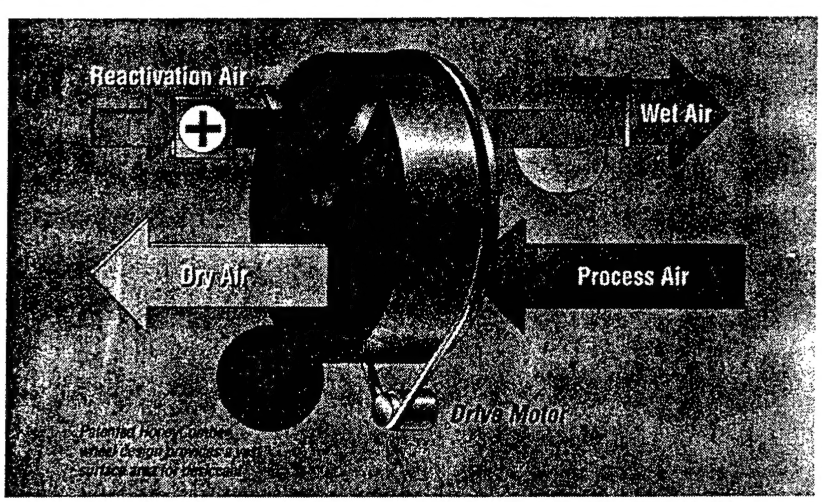

Figure 1. Desiccant wheel operation.

The second calculation made was the product load or cloth load, the analysis of how much moisture is carried by the cloth of the people entering the gymnasium. The personnel load (the moisture from respiration and perspiration) was also considered. The fourth analysis calculated the moisture that infiltrates through cracks, doors, and walls, because no building is hermetically sealed. The moisture from combustion, evaporation, and from air leaks through conveyors or air locks was omitted from this analysis because a gymnasium setting does not have these moisture sources.

The total internal moisture load was calculated for three different gymnasium uses (scenarios): games, classes, and practices. For some of the analyses (e.g., personnel load, cloth load, and infiltration through doors), the moisture that enters the gymnasium depends on the people entering the gymnasium. Therefore the total internal moisture will be different for each scenario. Also, an outside moisture load that enters from fresh air or make-up air must also be calculated. Because not all of the air inside of the gymnasium can be reused, introduction of outside air is necessary to maintain fresh air inside the gymnasium. After calculating each moisture load, the internal moisture load is added to the external moisture load to reach the total moisture load that enters the gymnasium.

3 Methodology

Before starting any design, the engineer must establish the design conditions. Table 1 lists the outside and inside design conditions for the AHS gymnasium. These numbers were calculated using ASHRAE Handbook, Fundamentals (ASHRAE 1997). In Puerto Rico, the dry bulb temperature (DB) is normally 90 °F, and the wet bulb temperature (WB) is 78 °F in the summer and 68 °F in the winter. This state will be considered the same for the interior-surrounding space, that is, for the halls and offices of the gymnasium. Using the psychometric chart of shown in Figure 2, the conditions for the outside moisture content was found to be 130 gr/lb. According to *The Dehumidification Handbook* (1990) "each gr/lb corresponds to 0.0067 in. of Hg." The outside vapor pressure was therefore calculated as the moisture content multiplied by 0.0067 in. of Hg, and the outside vapor pressure was calculated as 0.871 in. of Hg. The same procedure was repeated for the inside conditions. The standard comfort conditions for the inside of the gymnasium are a dry bulb temperature of 75 °F and 50 percent relative humidity. Using these two conditions in the psychometric chart, the inside moisture content was calculated as 60 gr/lb, and the vapor pressure at 0.402 in. of Hg. To calculate the total moisture load for the gymnasium, it was necessary to calculate and sum seven different types of moisture loads:

1. Moisture from permeation
2. Moisture from personnel
3. Moisture from cloth
4. Moisture from air leaks through cracks
5. Moisture from air leaks through walls
6. Moisture from air leaks through doors
7. Moisture from make up air.

Table 1. Outside and inside gymnasium conditions.

Condition	Temperature (DB) °F	Moisture Content (gr/lb)	Vapor Pressure (Hg)	Temperature (WB) °F	Relative Humidity (%)
Outside-Summer	90	130	0.871	78	60
Outside-Winter	68				
Interior-Surrounding Space to be Treated	90	130	0.871	78	60
Condition to be Maintained in Treated Space	75	60	0.402		50

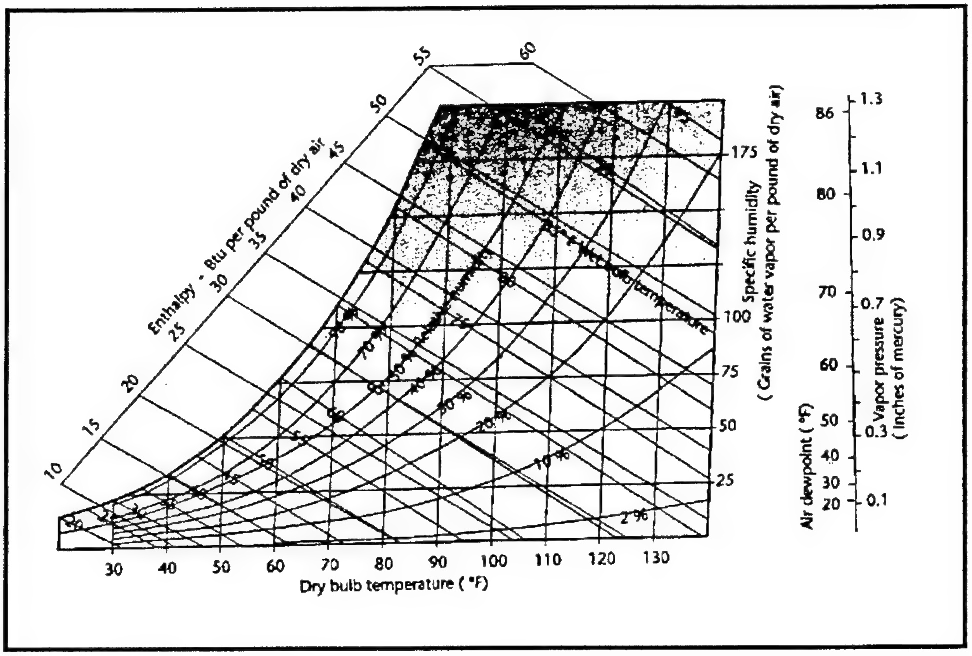

Figure 2. Psychometric chart.

Vapor Transmission into Dehumidified Space: Moisture from Permeation

To calculate the permeation moisture load, it is necessary to find the material permeance factor, the surface area, and the difference in vapor pressure across the given material. "Each material has a different permeance rating, according to how much water vapor it will pass per square foot in a given period of time at a given vapor pressure differential. Since moisture travels through air more quickly than through solids, the permeance factor strongly depends on porosity of the material" (Munters Cargocaire, MA. 1990). Water vapor moves through the materials at a rate proportional to the porosity and negatively proportional to the permeance factor. A material with a large porosity will have a large permeance factor. The gymnasium has four concrete block walls, a metal deck ceiling, and a concrete floor. Table A1 lists the permeance factor of each material.

The design drawings of the gymnasium gave sufficient measurement data to calculate the area of the walls, ceiling, and floor. The walls were 84 ft long and 24.25 ft high. The louvers on the walls were considered separately because they will be sealed with a material that has a very low permeance factor compared with the permeance factor of the concrete block. Each wall has a different number of louvers. The area of each louver was subtracted from the total area of the walls (so that each wall has a different area than that listed in Table 2). The area of the ceiling includes eight fans and 24 skylights, for a total area of 128 and 384 sq ft, respectively.

Table 2. Vapor transmission into dehumidified space: moisture from permeation

	Material	Permeance factor gr/hr/sq ft/in HgDVP		Area (sq ft)		D VP in Hg	gr./hr
Wall 1	Concrete block	2.4	X	1279	x	0.469	1439.65
Wall 2	Concrete block	2.4	X	1415	x	0.469	1593.11
Wall 3	Concrete block	2.4	X	1576	x	0.469	1773.95
Wall 4	Concrete block	2.4	X	1704	x	0.469	1918.02
Ceiling	Metal deck	0	X	6544	x	0.469	0
Floor	Concrete	0.4	X	7056	x	0.469	1323.71
						Wp Permeance	8048.4

The ceiling is 84 ft long and 84 ft wide, for an area of 7056 sq ft. This also differs from the area listed in Table 2, because the area of the fans and skylights were subtracted. The fans and skylights will be sealed with the same material as the louvers, which have a permeance factor of zero. The skylights also have a zero permeance factor, that is—no water vapor will pass through the ceiling, fans, or skylights. The floor was 84 ft long and it 84 ft wide, for an area of 7056 sq ft.

It was also important to calculate the difference in vapor pressure from the inside and outside of the gymnasium. This analysis depends on the difference in vapor pressure on either side of the material because water vapor moves through the walls at a rate proportional to the difference in vapor pressure. The difference in vapor pressure was calculated using the design conditions. For the outside of the gymnasium, the vapor pressure was 0.871 in. of Hg. For the inside of the gymnasium, the vapor pressure was 0.402 in. of Hg. The difference in vapor pressure was therefore 0.469 in. of Hg.

After calculating these results, it was possible to find the moisture load from each wall, from the ceiling and from the floor. To calculate the moisture from permeation, it is necessary to multiply the permeance factor, the area, and the difference in vapor pressure of each material, and then to sum the loads. In this particular case, the permeance moisture load was 8048.4 gr/hr.

Personnel Load: Moisture from Personnel

The essential part of calculating the personnel load is the water vapor and the moisture from respiration. In a gymnasium setting, the number of people entering the space and their activity level is crucial, because more active people will have different moisture loads than less active people. The number of people will depend on the setting: game, class, or practice, and the moisture evaporation will

depend on the degree of physical activity of each person. In each setting, some people will be seated, some at rest, some standing, some doing light work, and some doing moderate work. The moisture evaporation for each one was calculated using Figure B3. With an inside temperature of 75 °F, the moisture evaporation for people seated at rest was 700 gr/hr; for people standing, 2400 gr/hr; for people doing light work, 3500 gr/hr; and for people doing moderate work, 5500 gr/hr.

The number of people in each period varies. For a game period, there are (on average) 300 people inside the gymnasium. (The maximum capacity of the gymnasium is 400.) According to the AHS principal, an average of 30 students play in one game. A simple analysis estimates that 250 persons will watch a game, 10 persons will be standing, and 10 will be doing light work. In a class period there will be no people seated, 25 persons standing, 50 doing light work, and 175 doing moderate work. These numbers are based on the assumption that there are 50 students in each 1-hour class. Five of those are standing, 10 doing light work (e.g., walking), and 35 playing or doing moderate work. Each school day has five class periods so that each of the last numbers is multiplied by 5 to obtain the total people inside the gymnasium in 1 day. In a practice period only the team (about 30 individuals) uses the gymnasium. In this instance, no people are seated (at rest), an average of 5 people are standing, 5 doing light work, and 20 doing moderate work (Tables 3, 4, and 5). The personnel load for each activity state was calculated by multiplying the number of people by the moisture evaporation:

$$Wn = (Pa \times Fa) + (Pb \times Fb) + (Pc \times Fc) + (Pd \times Fd)$$

where:

Wn = the moisture from personnel

Pa, Pb, Pc, and Pd = the number of people seated at rest, standing, doing light work and doing moderate work, respectively

Fa, Fb, Fc, and Fd = the evaporation per person.

An analysis of each setting showed that the total moisture from personnel in a game setting was 399,000 gr/hr, in a class setting was 1,197,500 gr/hr, and in a practice setting was 139,500 gr/hr.

Table 3. Personnel load for a game period.

People watching game "A"	**250**	**Personnel load**	**175,000**
Moisture evaporation (gr/h r)	700	(# people*gr/hr)	
People standing "B"	**10**	**Personnel load**	**24,000**
Moisture evaporation (gr/hr)	2400	(# people*gr/hr)	
People doing Light Work "C"	**10**	**Personnel load**	**35,000**
Moisture evaporation (gr/hr)	3500	(# people*gr/hr)	
People playing "D"	**30**	**Personnel load**	**165,000**
Moisture evaporation (gr/hr)	5500	(# people*gr/hr)	
Temperature DB *F	75		
Total of people per day	**300**	**Wn (gr/hr):**	**399,000**

Table 4. Personnel load for a class period.

People seated at rest "A"	**0**	**Personnel load**	**0**
Moisture evaporation (gr/hr)	700	(# people*gr/hr)	
People standing "B"	**25**	**Personnel load**	**60,000**
Moisture evaporation (gr/hr)	2400	(# people*gr/hr)	
People doing Light Work "C"	**50**	**Personnel load**	**175,000**
Moisture evaporation (gr/hr)	3500	(# people*gr/hr)	
People doing Moderate Work "D"	**175**	**Personnel load**	**962,500**
Moisture evaporation (gr/hr)	5500	(# people*gr/hr)	
Temperature DB *F	75		
Total of people per day	250		
Total of people per hour	**50**	**Wn (gr/hr):**	**1,197,500**

Table 5. Personnel load for a practice period.

People seated at rest "A"	**0**	**Personnel load**	**0**
Moisture evaporation (gr/hr)	700	(# people*gr/hr)	
People standing "B"	**5**	**Personnel load**	**12000**
Moisture evaporation (gr/hr)	2400	(# people*gr/hr)	
People doing Light Work "C"	**5**	**Personnel load**	**17500**
Moisture evaporation (gr/hr)	3500	(# people*gr/hr)	
People doing Moderate Work "D"	**20**	**Personnel load**	**110000**
Moisture evaporation (gr/hr)	5500	(# people*gr/hr)	
Temperature DB *F	75		
Total of people per day	**30**	**Wn (gr/hr):**	**139500**

Product Load: Moisture from Cloth

Moist material brought into the gymnasium also affects the moisture load. The most common moist material that generally enters a gymnasium is clothing. If a solid material is dryer than its surrounding it will absorb the moisture in the air; if the air is dryer than the material, the material will liberate moisture. This process is due to the difference in vapor pressure between the material and its surroundings. When a moist material enters the gymnasium, it will give up moisture until the vapor pressure between the material and the air is the same. Each material must be treated differently to calculate how much moisture it can bring into the space. Figure B4 shows the equilibrium moisture contents of some materials when the space temperature is 75 °F. The general formula to calculate the moisture that will enter the gymnasium from clothing is:

$$Wpp = (lb/hr) \times (pw2 - pw1)$$

where:

Wpp = the water vapor from clothing in lb/hr

(lb/hr) = the total mass of material entering the room every hour

pw2 = the equilibrium moisture content of material before entering the gymnasium (lb/hr)

pw1 = the equilibrium moisture content of material inside the gymnasium (lb/hr).

Cotton is one of the most common cloth materials used in Puerto Rico, especially in school uniforms. For this reason, cotton was studied as the cloth material. To begin the analysis, it was necessary to find the equilibrium moisture content of material before entering the gymnasium (pw1). This was calculated using Figure B4 and the outside conditions. Assuming a relative humidity of 60 percent and cotton as the material, the moisture content was 0.07 lb/lb. The equilibrium moisture content of the material inside of the gymnasium (pw2) was also calculated using Figure C3, along with inside conditions. Assuming a relative humidity of 50 percent and cotton material, the moisture content was calculated as 0.06 lb/lb. It is also necessary to calculate the total mass of the material entering the gymnasium. This amount will depend of the setting or period, because it depends on how many people enter the gymnasium in 1 hour. For a game period the total people entering the gymnasium is 150 and the weight of the cloth per person is an average of 2 lb, therefore the total mass entering the gymnasium in 1 hour was 300 lb/hr. For a class period the total people entering the space in 1 hour is 50, and the total mass that enters the gymnasium is 100 lb/hr. In the practice period the people that will enter the gymnasium in 1 hour is 30, there-

fore the total mass of material is 60 lb/hr. These calculations are shown in Tables 6, 7, and 8. The total moisture from cloth was calculated using the given formula, and then by multiplying the result by 7000, to convert lb/hr to grains/hr. For a game period, the moisture load was 21000 gr/hr; for a class period, it was 7000 gr/hr; and for the practice period, it was 4200 gr/hr.

Moisture from Combustion and Moisture Evaporated from Wet Surfaces

In spaces where open gas burners are used for heat and to process food, the moisture that results from combustion and the evaporation from the wet surfaces can add significant loads. This is not the case in a high school gymnasium where there are no open gas burners or wet surfaces. Therefore, these moisture loads were not calculated.

Table 6. Product load: moisture from cloth in a game period.

Parameter	Measure
*Temperature outside the Gym *F*	*90*
Relative Humidity outside the Gym %	60
Equilibrium moisture content of material before entering the Gym (pw1) lb/lb	0.07
*Temperature inside the Gym *F*	*75*
Relative Humidity inside the Gym %	50
Equilibrium moisture content of material inside the Gym (pw2) lb/lb	0.06
People entering the Gym in one hr:	*150*
Weight of cloth (cotton) per person (lb):	2
Total mass of material entering the room in one hr (lb/hr):	300
Wpp=lb/hr*(pw1-pw2)=	3.00
Note:	
To convert lb/hr to gr/hr multiply by 7000	
Wpp in gr/hr=	21000

Table 7. Product load: moisture from cloth in a class period.

Parameter	Measure
*Temperature outside the Gym *F*	*90*
Relative Humidity outside the Gym %	60
Equilibrium moisture content of material before entering the Gym (pw1) lb/lb	0.07
*Temperature inside the Gym *F*	*75*
Relative Humidity inside the Gym %	50
Equilibrium moisture content of material inside the Gym (pw2) lb/lb	0.06
People entering the Gym in one hr:	50
Weight of cloth (cotton) per person (lb):	2
Total mass of material entering the room in one hr (lb/hr):	100
Wpp=lb/hr*(pw1-pw2)=	1.00
Note:	
To convert lb/hr to gr/hr multiply by 7000	
Wpp in gr/hr=	7000

Table 8. Product load: moisture from cloth in a practice period.

Parameter	Measure
*Temperature outside the Gym *F*	*90*
Relative Humidity outside the Gym %	60
Equilibrium moisture content of material before entering the Gym (pw1) lb/lb	0.07
*Temperature inside the Gym *F*	*75*
Relative Humidity inside the Gym %	50
Equilibrium moisture content of material inside the Gym (pw2) lb/lb	0.06
People entering the Gym in one hr	*30*
Weight of cloth (cotton) per person (lb):	2
Total mass of material entering the room in one hr (lb/hr):	60
Wpp=lb/hr*(pw1-pw2)=	0.60
Note:	
To convert lb/hr to gr/hr multiply by 7000	
Wpp in gr/hr=	4200

Moisture from Air Leakage through Cracks

Cracks are an important part of the moisture load calculation, and must be considered because no building is hermetically sealed. Moisture enters the gymnasium via air leaks through cracks. This analysis considered three types of air leak locations: cracks in doors (frames), cracks in louvers (frames), and cracks in fans (frames). The moisture load was calculated separately for each case.

Each analysis considered the air leakage rate through the crack, the length of the crack, the air density, and the difference in moisture content between the inside and outside. The following formula calculates the moisture carried through cracks in an exterior wall:

$$Wi = Q \times d \times (Mo\text{-}Mi) \times L$$

where:

Wi	=	the moisture load
Q	=	the air leakage rate
D	=	the air density
(Mo-Mi)	=	the difference in moisture content and L is the crack length.

This formula was used to find the moisture load for each case. Table A2 was also used to find the air leakage through door frames, assuming cracks with an average width of ¼ in. and a wind velocity in Puerto Rico of approximately 10 mph or 880 fpm (ASHRAE 1997). The air leakage rate through door frames was therefore calculated as 515 cu ft/hr/ft. The same process was used to find the air leakage rate through the louver frames (because the gymnasium's louvers will be sealed before installing the system). Figure 3 shows a gymnasium door and an (unsealed) louver. Measurement of moisture load for the louver frames assumed cracks with a 1/8-in. width. As before, the air leakage rate for the louver frames was calculated as 255 cu ft/hr/ft. The calculation for the fan frames assumed cracks with a depth of 1/16 in. for an air leakage rate of 130 cu ft/hr/ft.

The length of each crack was calculated from the length of each frame, using data taken from the design drawings (Table 9). Four of the door frames (the double doors) had a crack of 39.33 ft, and two of the doors (the single doors) had a crack length of 23.66 ft. The length of the louver frames varied with the quantity of louvers in each wall or door. The first wall had 16 louvers with a total crack length of 400 ft. The second wall had 12 louvers with a crack length of 300 ft. There were 10 louvers in the third wall with a crack length of 250 ft. The fourth wall had 8 louvers with a crack length of 200 ft. Two of the double doors also had louvers. Each of these doors had six louvers and a crack length of 90 ft.

Table 9. Infiltration load: moisture from cracks.

Location	No. of cracks	Air Leakage Rate (cu ft/hr/ft)	Length of Crack (ft)	Air Density	D gr/lb	gr/hr
Cracks in door frames						
Door 1	1	515	39.33	0.075	70	106,338
Door 2	1	515	39.33	0.075	70	106,338
Door 3a	1	515	39.33	0.075	70	106,338
Door 3b	1	515	23.66	0.075	70	63,971
Door 3c	1	515	23.66	0.075	70	63,971
Door 4	1	515	39.33	0.075	70	106,338
Cracks in louver frames						
	Number of Louvers					
Wall 1	16	255	400	0.075	70	8,568,000
Wall 2	12	255	300	0.075	70	4,819,500
Wall 3	10	255	250	0.075	70	3,346,875
Wall 4	8	255	200	0.075	70	2,142,000
Door 1	6	255	90	0.075	70	725,495
Door 2	6	255	90	0.075	70	725,495
Cracks in fan frames						
	Number of Fans					
Ceiling	8	130	16	0.075	70	87,360
					Total WI=	20,968,021

An air density nomograph (shown in Figure B2) was used to calculate the air density for different regions. The air density in Puerto Rico is approximately 0.075. This value was used to calculate the infiltration load through cracks in doors, louvers, and fans. The calculation for the difference in moisture content was also used in cracks in doors as in louvers and fans walls. For the outside, the moisture content was 130 gr/lb and for the inside it was 60 gr/lb, therefore the difference in moisture content was 70 gr/lb. The infiltration load for each case was calculated using this formula. The sum of all results yields the total load from infiltration through cracks, or 20,968,021 gr/hr.

Moisture from Air Leakage through Doors

When any door opens, it creates local, short-term pressure differences and air turbulence that can pull in moisture inside the space. To calculate this moisture load, one must consider the area of the door, wind velocity, air density, the difference in moisture content, and the time (minutes per hour) that the door is open. This last item will be different for each of the three activity scenarios in the gymnasium moisture analysis. This moisture load was calculated separately for game, class, and practice periods (Tables 10, 11, and 12).

Table 10. Infiltration load: moisture from doors in a game period

	Area of Door (sq ft)	Wind Velocity (fpm)	Air Density	Minutes Open/hr*	Air moisture Outside (gr/lb)	Air moisture Inside (gr/lb)	gr/hr
Door 1	61	880	0.075	20	130	60	5,667,200
Door 2	61	880	0.075	0	130	60	0
Door 3a	61	50	0.075	20	130	60	320,250
Door 3b	30	50	0.075	2	130	60	15,750
Door 3c	30	50	0.075	2	130	60	15,750
Door 4	61	880	0.075	0	130	60	0
						Total Wi=	6,018,950

Table 11. Infiltration load: moisture from doors in a class period.

	Area of Door (sq ft)	Wind Velocity (fpm)	Air Density	Minutes Open/hr*	Air Moisture Outside(gr/lb)	Air Moisture Inside (gr/lb)	gr/hr
Door 1	61	880	0.075	10	130	60	2,833,600
Door 2	61	880	0.075	0	130	60	0
Door 3a	61	50	0.075	10	130	60	160,125
Door 3b	30	50	0.075	1	130	60	7,875
Door 3c	30	50	0.075	1	130	60	7,875
Door 4	61	880	0.075	0	130	60	0
						Total Wi=	3,009,475

Table 12. Infiltration load: moisture from doors in a practice period.

	Area of Door (sq ft)	Wind Velocity (fpm)	Air Density	Minutes Open/hr*	Air Moisture Outside (gr/lb)	Air Moisture Inside (gr/lb)	gr/hr
Door 1	61	880	0.075	5	130	60	1,416,800
Door 2	61	880	0.075	0	130	60	0
Door 3a	61	50	0.075	5	130	60	80,063
Door 3b	30	50	0.075	0	130	60	0
Door 3c	30	50	0.075	1	130	60	7,875
Door 4	61	880	0.075	0	130	60	0
						Total Wi=	1,504,737

The following formula was used to calculate the moisture from air leaks through doors:

Wi = (air flow velocity) x (open area) x (air density) x (time open)
x (air moisture outside-air moisture inside)

For all the periods, these numbers will be the same except when each door is open. Since this number is different for each activity setting, it was calculated first. Doors are most often opened in a game period, because during games, more people enter the gymnasium in less time. The number of minutes the doors were opened was analyzed by estimating how many people enter gymnasium during

the game. The game period last 4 hours (2 hours of play, 1 hour to arrive, and 1 hour to leave). During the first and the last hour, people open the doors at a higher rate (about 30 min/hr). During the 2 hours of play, there is less movement. (The door opens on average about 10 min/hr.) These calculated times were summed and averaged. The sum of 80 min/hr in 4 hours averages to a rate of 20 min/hr. The two exiting doors are not in use during the school year, and two other doors enter the coaches' offices. The coaches' doors are not used often during games, only about 2 min/hr. A similar analysis estimated these rates for class and practice periods. Class periods last 5 hours a day. The average rate of entries for this period was 10 min/hr for the exiting doors and 1 min/hr for each of the coaches' offices. For practice periods, the rate of people entering the gymnasium is the lowest, comparing to the other two settings. Practices last 3 hours, 5 days a week. The average rate of door opening during practices was 5 min/hr for the exiting doors, and 1 min/hr for only one coach office. The other office was not considered because only one coach supervises any practice session.

The design drawings provided sufficient measurements to find the area of the doors. The area of the exit doors' was 61 sq ft. The area of the doors to the coaches' offices (single doors) was 30 sq ft. The air density for Puerto Rico is 0.075, the moisture content outside the gymnasium is 130 gr/lb, and the moisture content inside the gymnasium is 60 gr/lb. There is also a wind velocity of 10 mph, or 880 fpm. The wind velocity was not considered for the calculation of the coaches' offices, because this specific data was not available. According to *The Dehumidification Handbook,* "if a door opens to another space [not the outside], assume there is an air current of 50 ft per minute into the room for the time the door remains open, unless there is better specific data available." Using this formula, the infiltration load through each door for each setting was calculated and summed to give the final results (Tables 10, 11, and 12).

Moisture from Air Leakage through Walls

It was important to analyze the infiltration passing through walls. The area of each wall, the air density, the difference in moisture content, and the air leakage rate must be considered. The formula to find the infiltration load through wall is:

Wi = (surface area) x (air leakage rate) x (moisture outside-moisture inside) x (air density).

Table 13. Infiltration load: moisture from walls.

	Air leakage rate (cu ft/hr/ft)	Wall Area (sq ft)	Air density	D (gr/lb)	gr/hr
Wall 1	0.09	1279	0.075	70	604.3
Wall 2	0.09	1415	0.075	70	668.7
Wall 3	0.09	1576	0.075	70	744.7
Wall 4	0.09	1704	0.075	70	805.1
				Total Wi=	2822.9

The drawing designs provided sufficient detail to calculate the surface areas. The area of the louvers was subtracted from the area of each wall, which explains the difference between the calculated and measured areas (see Table 13). The air density and the difference in moisture content are the same as discussed before: 0.075 and 70 gr/lb, respectively. Table A2 was used to find the air leakage rate. For a wall with three coasts of plaster and a wind velocity of 10 mph, the air leakage rate was 0.09 cu ft/hr/ft. After calculating the infiltration load for each of the four walls with the formula, the final result was a load of 2822.9 gr/hr.

Review of the Data: Internal Moisture Loads

To calculate total moisture load, it was first necessary to calculate the internal moisture loads. Table 14 lists these internal moisture loads.

Table 14. Review of the data: internal moisture loads.

Source	Game	Class	Practice
Permeation	8048.4	8048.4	8,048.4
Cloth	21000	7000	4,200
Personnel	399000	1197500	139,500
Combustion	None	None	None
Evaporation	None	None	None
Air leaks:			
Conveyors	None	None	None
Air Lock	None	None	None
Cracks	20968021	20968021	20,968,021
Walls	2822.9	2822.9	2,822.9
Doors	6018950	3009475	1,504,737
Total Wint	27417843	25192868	22,627,330

Moisture from Make-Up Air

The internal moisture loads are the ones that come from inside the gymnasium. However, generally the largest amount of moisture that enters the gymnasium is the introduction of makeup air (usually called "fresh air"). Fresh air is introduced into the system "to provide ventilation for people and make-up air for exhaust hoods and fans, and/or to maintain a positive air pressure in the room compared to the surrounding environment" (Munters Cargocaire 1990). This air comes from outside of the gymnasium. The moisture that is carried by this air will be removed by the system before it enters the room.

This moisture load was calculated by measuring the air density, the moisture inside the room, the moisture level outside the room, and the air flow rate required to remove the moisture. Note that standards establish a minimum fresh air requirement of 15 to 25 cu ft per minute per person. This standard of 25 cfm per person was used to calculate the air flow rate. The number of people inside the space vary with the activity period in a gymnasium. If there are 300 people in a game, the air flow rate must be 7500 cfm; if there are 50 people in a class, it must be 1250 cfm; in a practice of 30 people, the air flow rate has to be 750 cfm. Table 15 shows the final results for the outside moisture load, for each setting, converted from gr/min to gr/hr.

Total Moisture Load

The total moisture load that will enter the gymnasium is the sum of the internal load added to the external moisture load. That is, the moisture that comes from permeation, cloth, people, cracks, doors, and walls was added to the moisture that enters with fresh air. Table 16 lists three different results for each setting.

Table 15. Moisture from make up air.

	Air density (lb/cu ft)	Moisture Inside Room (gr/lb)	Moisture level Outside Room (gr/lb)	Air flow rate to remove the moisture (cfm)	Minutes per Hour	Moisture load from fresh air (gr/hr)
Game	0.075	60	130	7500	60	2,362,500
Class	0.075	60	130	1250	60	393,750
Practice	0.075	60	130	750	60	236,250

Table 16. General results.

Setting	Internal Moisture Load	External Moisture Load	Total Moisture Load
Game	27,417,843	2,362,500	29,780,343
Class	25,192,868	393,750	25,586,618
Practice	22,627,330	236,250	22,863,580

4 Conclusions

This study has calculated the moisture load for the AHS gymnasium, Fort Buchanan, Puerto Rico, as a preliminary step to implementing a desiccant cooling system. The analysis considered the moisture that comes from permeation, people, and cloth; air leaks through cracks, walls, and doors; and the moisture that comes from make up air in three different settings: games, classes and practices. The first calculations comprise the internal moisture load, and the last one comprises the external moisture load. The total moisture load for the AHS gymnasium was 29,780,343 gr/hr for a game scenario, 25,586,618 gr/hr for a class scenario, and 22,863,580 gr/hr for a practice scenario.

The results of this analysis show that the peak moisture load occurs during game periods (currently once a week). However, it is important to note that, after the gymnasium is air-conditioned, activities may be scheduled more frequently. Another increase in activity may occur after the summer of 1999, when the Headquarters, U.S. Army South will be established at Fort Buchanan.

The final moisture load could be reduced by lessening the moisture load due to cracks. This could be accomplished by improving the joint seals around the ventilation louver covers. However, this may not be a practical solution because the louvered covers must be easily removable to service the air-conditioning system. This is also true for the covers on the roof mounted ventilation fans.

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Munters Cargocaire, *The Dehumidification Handbook*, 2d ed. (Munters Cargocaire, MA, 1990).

Department of Energy, *Introduction to the Advanced Desiccant Cooling and Dehumidification Program*, found at URL: http://www.nrel.gov/desiccantcool/intro.htm

Appendix A: Supplementary Tables

Table 5-1*
List of Permeance Factors

BUILDING MATERIAL PERMEANCE FACTORS[1]
grains/hr/sq ft/in HgΔV.P.

DESCRIPTION OF MATERIAL OR CONSTRUCTION	PERMEANCE No Vapor Seal	PERMEANCE With Vapor Retarder Paint (perm = .45)
MATERIALS USED IN CONSTRUCTION		
Brick, 4 inch Masonry	0.8	0.29
Brick, 8.5 inch Masonry	0.38	0.21
Concrete, 1:2:4 mix, 8 inch	0.40	0.21
Concrete, 1:2:4 mix, 1 inch[2]	3.20	—
Concrete Block, 8 inch	2.40	0.38
Plaster on Metal Lath, ¾ inch	15	0.44
Plaster on Gypsum Lath (with studs)	20	0.44
Gypsum Wall Board, Plain ⅜ inch	50	0.45
Insulating Board, Sheathing, 1 inch[2]	50	—
Hardboard (standard), ⅛ inch	11	0.43
Plywood, Exterior Glue, ¼ inch	0.35	0.20
Plywood, Interior Glue, ¼ inch	0.94	0.30
Wood, Sugar Pine, 1 inch[2]	5.3	—
INSULATION MATERIALS		
Air (still), 1 inch[2]	120	
Corkboard, 1 inch[2]	9.1	
Fibrous Insulation (unprotected), 1 inch[2]	116	
Expanded Polyurethane Board, 1 inch[2]	1.6	
Expanded Polyurethane (extruded), 1 inch[2]	1.2	
VAPOR BARRIER MATERIALS		
Aluminum foil, .002 inches	.025[3]	
Polyethylene, .002 inches	.16	
Polyethylene, .006 inches	.06	
Metal Deck, Built-up Roofs	0.0	
PAPER, FELTS		
Saturated and Coated Roll Roofing, 65 lb/100 sq ft	0.24	
Insulation Back-up Paper, Asphalt Coated	4.2	
Asphalt Coated Vapor Retarder Paper	0.6	
15 lb Asphalt Felt	5.6	
18 lb Tar Felt	18.2	
Single-Kraft, Double Layer	42	
PAINTS AND COATINGS		
Latex Vapor Retarder Paint, .003 inch	.45	
Commercial Latex Sealer, .0012 inch	6.28	
Various Primers plus 1 Coat Flat Oil Paint On Plaster	3.0	
2 Coats Aluminum Paint, Estimated	0.8	
2 Coats Asphalt Paint, Estimated	0.4	
2 Coats Flat Paint of Interior Insulation Board	4	

NOTES:
1. Values shown above are estimates **only** based on a variety of test methods. When a range or more than one value is available, the higher value is shown. Contact manufacturer of materials being considered for exact values.
2. Permeance at a different thickness t, in inches, may be determined from the permeance value for 1 inch thickness by multiplying by the factor 1/t.
3. Permeance value shown is based on damage (pinholes) which may occur in handling.

*Cargocaire Table, primarily adapted from ASHRAE Handbook of Fundamentals, 1981, Chapter 21

Table 5-1
Building material permeance factors
The thickness of the material is not as influential as porosity. A plastic film only .006 inches thick is 40 times more effective in retarding vapor flow than a concrete block measuring 8 inches thick.

Table A1. Building material permeance factor.

5—12

Table 5 - 3 Air Leakage Through Cracks (cu.ft./hr/linear ft.)

mph	1	2.5	5	10	15	20
fpm	88	220	440	880	1350	1750
In. wc.	0.0005	0.003	0.012	0.048	0.11	0.193
Older Windows						
Wood, Double-hung						
Loose fit	3	8	20	49	81	122
Non-weather stripped, avg. fit	1	3	7	17	28	43
Weather stripped, avg. fit	0.5	1.5	4	9	15	23
Wood Casement						
Weather stripped	0.2	0.6	1.5	4	6	9
Metal						
Casement, pivoted	6	18	43	108	176	262
Double-hung, no w.s.	2.5	8	19	47	77	114
Double-hung, w.s.	1	3	8	19	32	47
Newer Windows						
Wood & Metal, most types	0.5	1.5	3.6	9	15	22
Storm Windows	*In combination with above, reduce values by 40%*					
Doors						
Sliding						
Aluminum	1.5	4	10	26	43	64
Wood	0.7	2	5	13	21	31
Hinged						
Well-fitted	0.5	1.3	3	8	13	19
Well-fitted, w.s.	0.3	0.8	2	4	7	11
Poorly fitted - 1/16" crack	5	16	40	100	158	240
Door & Window Frames						
Masonry wall, uncaulked	0.5	2	4	10	18	26
Masonry wall, caulked	0.1	0.4	0.8	1.5	3	5
Wood frame wall	0.5	1.5	3.5	9	14	21
Cracks						
1/16"	7	23	53	130	217	315
1/8"	13	45	105	255	435	630
1/4"	25	90	210	515	865	1260
Brick						
8.5" Plain	0.35	1	2.6	5	9	16
8.5" Plain with 2 coats of plaster	n/a	0.01	0.025	0.05	0.08	0.14
13" Plain	0.3	0.95	2.3	5	8	14
13" Plain w. 2 coats of plaster	n/a	n/a	n/a	0.01	0.04	0.05
13" with furring, lath & plaster	0.01	0.03	0.08	0.3	0.25	0.46
Frame Wall						
3 coats of plaster	0.01	0.02	0.04	0.09	0.16	0.22
Metal Walls						
Tight Joints	n/a	n/a	0.013	0.03	0.05	0.08
Average Joints	n/a	0.015	0.04	0.09	0.17	0.23
Loose joints	0.01	0.03	0.08	0.19	0.33	0.46

Cargocaire table, adapted primarily from ASHRAE Handbook of Fundamentals 1989, Chapter 23

C H A P T E R   F I V E

Table A2. Air leakage through cracks and walls.

Appendix B: Supplementary Figures

CARGOCAIRE
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CUSTOMER ______ APPLICATION ______
ADDRESS ______ CITY ______ STATE ______ ZIP ______
CUSTOMER CONTACT ______ TITLE ______ TEL. ______
INSTALLATION SITE ______ ALTITUDE (above sea level) ______ ft.

MOISTURE LOAD CALCULATION WORKSHEET

Instructions and applicable reference material may be found in Chapter 5 of The Dehumidification Handbook.

APPLICATION DESCRIPTION ______

LOCATION ______

OUTSIDE AND INSIDE BUILDING DESIGN CONDITIONS

CONDITION	CONDITIONS @ ______ in Hg BAROMETER			
	TEMPERATURE (DB) °F	MOISTURE CONTENT grains/lb	VAPOR PRESSURE in Hg	OTHER
Outside — Summer				
Outside — Winter				
Interior — Surrounding Space to be Treated				
Condition to be Maintained in Treated Space				
Ground or Well Water Temperature				

OTHER IMPORTANT FACTORS AND REMARKS

VAPOR TRANSMISSION INTO DEHUMIDIFIED SPACE
(Select PERMEABILITY FACTORS from TABLE 5-1)

	MATERIAL	PERMEANCE FACTOR	AREA sq ft	Δ V.P. in Hg*	grains/hr
Wall 1			x	x	=
Wall 2			x	x	=
Wall 3			x	x	=
Wall 4			x	x	=
Ceiling			x	x	=
Floor			x	x	=

W_p = ______ grains/hr

PERSONNEL LOAD
(Select PERSONNEL LOAD FACTOR from FIGURE 5-1)
W_n = ______ No. of People × ______ grains/hr/person FACTOR = ______ grains/hr

PRODUCT LOAD, INCLUDING PACKAGING MATERIAL
Load, in grains/hr, should be specified. For guidance, see FIGURE 5-2.
Product and Packaging Material Load = Rate × (Moisture Content of Material Entering Treated Space − Moisture Content of Material Removed from Treated Space)
W_{pp} = ______ grains/hr

FROM OPEN GAS FLAME
W_g = ______ cu ft/hr × 650 grains/cu ft = ______ grains/hr

EVAPORATION FROM WATER SURFACE (Use EVAPORATIVE RATE FACTORS from FIG. 5-4)
$W_e = \frac{[\_\_\_\_ \text{ sq ft}][\_\_\_\_ H_i \text{ or } H_o][\_\_\_\_ \Delta \text{V.P. in Hg}][7000]}{[\_\_\_\_ H_L]}$ = ______ grains/hr

*Δ V.P. in Hg = V.P. at Outside Surface of Wall − V.P. in Treated Space.

INFILTRATION LOADS (Determine "d" — density from NOMOGRAPH, FIGURE 5-5)

CONVEYORS (Base on Continuous Operation)
______ fpm Conveyor Speed × ______ ft² Net Open Area = ______ cfm
______ cfm × ______ "d" × 60 × ______ Δ grains/lb** = ______ grains/hr ①

DOORS (Use VELOCITY FACTORS from TABLE 5-2)
______ fpm Velocity × ______ sq ft = ______ cfm
______ cfm × ______ "d" × ______ minutes open/hr × ______ Δ grains/lb** = ______ grains/hr ②

AIR LOCK OR VESTIBULE
______ cu ft × ______ "d" × ______ openings/hr × ______ Δ grains/lb** = ______ grains/hr ③

CRACKS (Doors and Windows — Use TABLE 5-3)
______ cu ft/hr/ft × ______ ft of Crack × ______ "d" × ______ Δ grains/lb** = ______ grains/hr ④

WALLS (Use TABLE 5-4)
______ cu ft/hr/ft × ______ sq ft of Walls × ______ "d" × ______ Δ grains/lb** = ______ grains/hr ⑤

CAUTION: Ducting must be airtight, otherwise infiltration into ducting must be determined. = ______ grains/hr ⑥

TOTAL INFILTRATION LOAD
W_i = ① + ② + ③ + ④ + ⑤ + ⑥ = ______ grains/hr

INTERNAL MOISTURE LOAD
$W_{mi} = W_p + W_n + W_{pp} + W_e + W_g + W_i$ = TOTAL ______ grains/hr

MAKE-UP AIR LOAD
For guidance, see TABLE 5-5. Make-up air shall be adequate to cover the (1) Exhaust or (2) Personnel and Process Air Requirements WHICHEVER IS GREATER.
W_m = ______ cfm × ______ "d" × 60 × ______ Δ grains/lb** = ______ grains/hr

TOTAL MOISTURE LOAD
$W_{tot} = W_{mi} + W_m$ = TOTAL ______ grains/hr
(To convert grains/hr to pounds/hr, divide by 7,000)

**Δ grains/lb = Uncontrolled − Controlled Moisture Content

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Figure B1. Cargocaire worksheet.

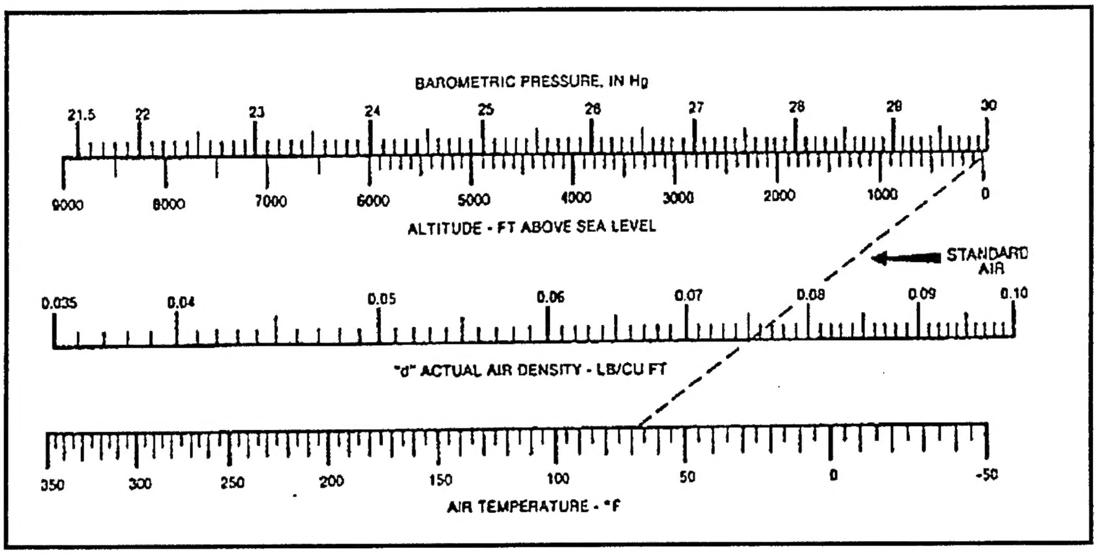

Figure B2. Air density nomograph.

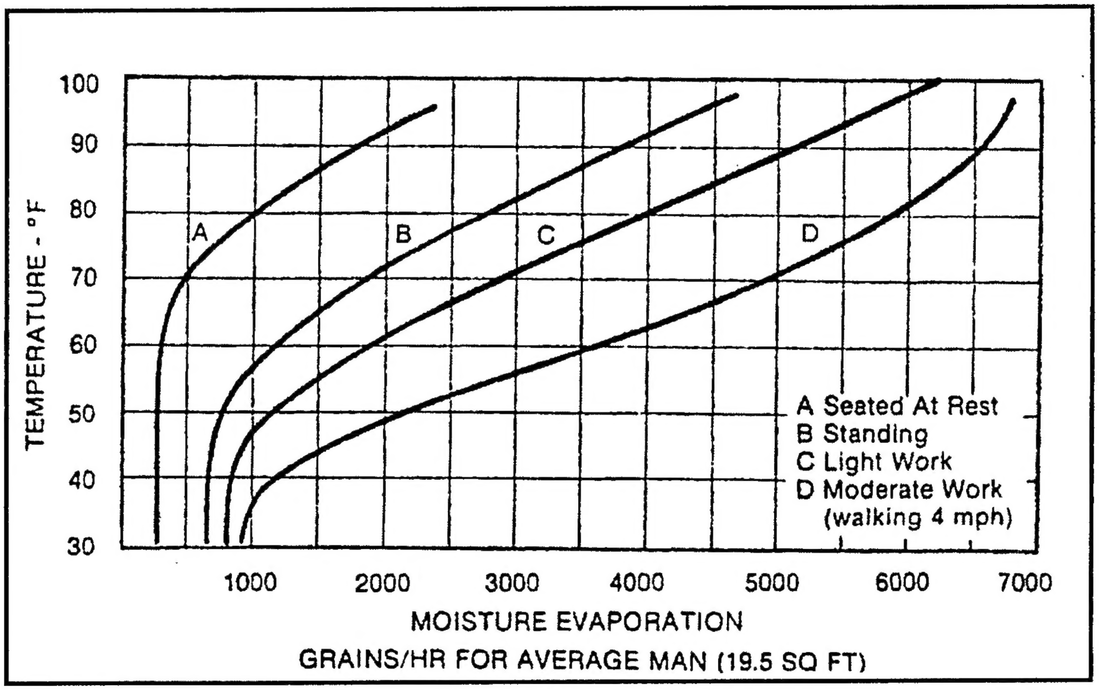

Figure B3. Moisture infiltration from occupants.

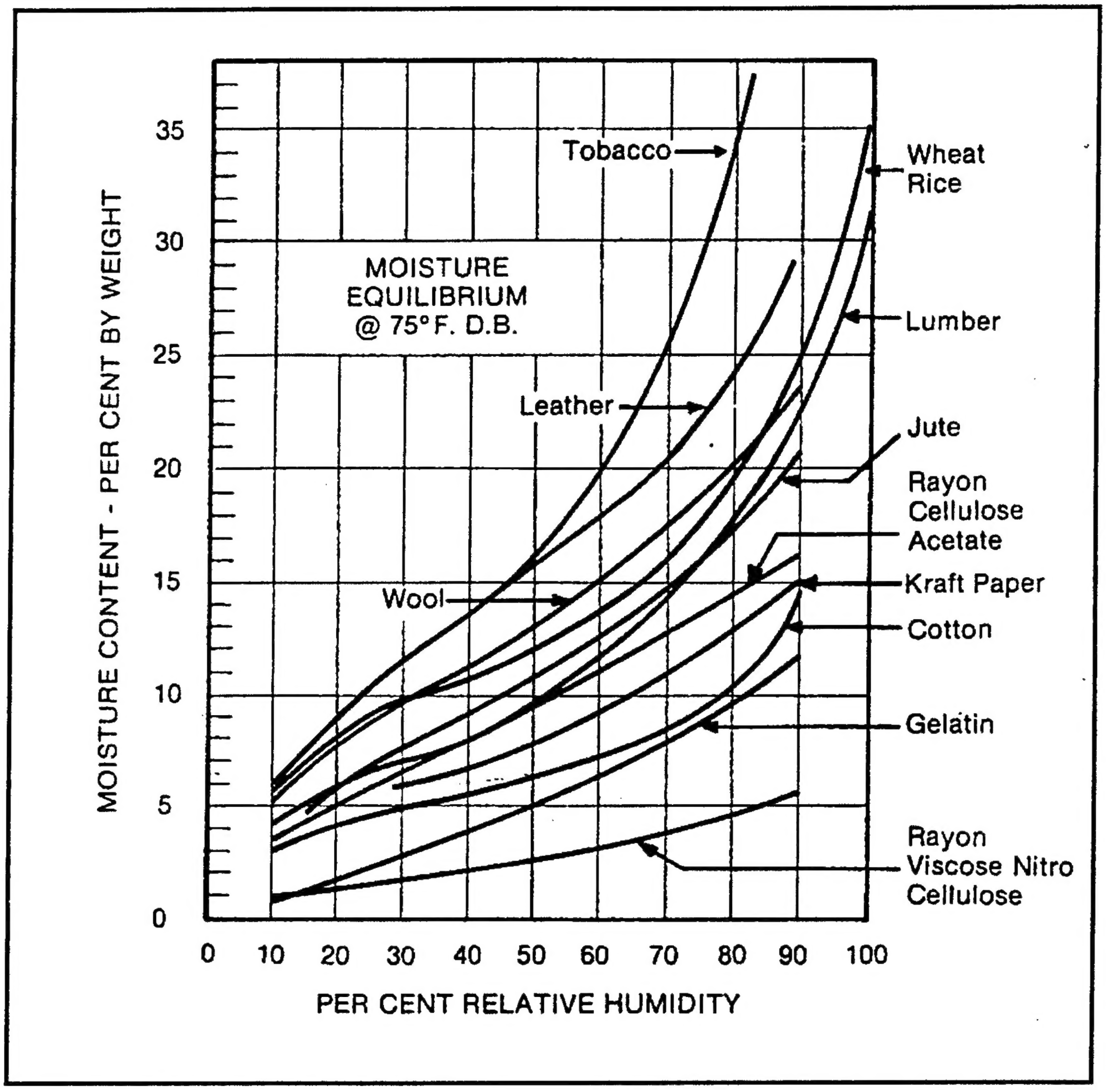

Figure B4. Moisture infiltration from cloth.

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 01-2000

2. REPORT TYPE Final

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Assessment for Desiccant Cooling Air-Conditioning at Antilles High School, Fort Buchanan, Puerto Rico: Moisture Load Analysis of the Gymnasium Building

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jaynary Barreto-Acobe and Martin J. Savoie

5d. PROJECT NUMBER
MIPR

5e. TASK NUMBER
HEPRAN-99RCL1031

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratory (CERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL TR-00-3

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Antilles Consolidated School System
ATTN: Facilities Engineering
Fort Buchanon, PR 00934-5000

10. SPONSOR/MONITOR'S ACRONYM(S)
Facilities Engineering

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

14. ABSTRACT

The U.S. Army Engineer Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL) was requested to independently assess the heating, ventilation, and air-conditioning (HVAC) system and related controls at Antilles High School (AHS), Antilles Consolidated School System, Fort Buchanan, Puerto Rico, and to help design a new air-conditioning system for the high school gymnasium. Due to the high temperature and high relative humidity common to Puerto Rico, it is desirable to implement an air-conditioning system that can maintain a controlled temperature of 75 °F and a 50 percent relative humidity. A "desiccant cooling" system was considered for this application because it can dehumidify the air entering the treated space, reduce the relative humidity, and result in lower operating costs than could a comparable conventional system. A necessary preliminary step before specifying a desiccant cooling system is to perform a moisture load analysis of the area to be cooled. This study documents the moisture load analysis of the gymnasium Building at AHS.

15. SUBJECT TERMS
gymnasium, air conditioning, desiccant cooling, Fort Buchanon, PR, HVAC, moisture load analysis

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Martin J. Savoie
Unclassified	Unclassified	Unclassified	SAR	36	19b. TELEPHONE NUMBER (include area code) (217) 373-6762